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The feasibility of renewable energies at an off-grid community in Canada

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ABSTRACT

Three renewable energy technologies (RETs) were analyzed for their feasibility for a small off-grid research facility dependent on diesel for power and propane for heat. Presently, the electrical load for this facility is 115 kW but a demand side management (DSM) energy audit revealed that 15–20% reduction was possible. Downsizing RETs and diesel engines by 15 kW to 100 kW reduces capital costs by $27 000 for biomass, $49 500 for wind and $136 500 for solar.

The RET Screen International 4.0® model compared the economical and environmental costs of generating 100 kW of electricity for three RETs compared to the current diesel engine (0 cost) and a replacement ($160/kW) diesel equipment. At all costs from $0.80 to $2.00/l, biomass combined heat and power (CHP) was the most competitive. At $0.80 per liter, biomass' payback period was 4.1 years with a capital cost of $1800/kW compared to wind's 6.1 years due to its higher initial cost of $3300/kW and solar's 13.5 years due to its high initial cost of $9100/kW. A biomass system would reduce annual energy costs by $63 729 per year, and mitigate GHG emissions by over 98% to 10 t CO_2 from 507 t CO_2. Diesel price increases to $1.20 or $2.00/l will decrease the payback period in years dramatically to 1.8 and 0.9 for CHP, 3.6 and 1.8 for wind, and 6.7 and 3.2 years for solar, respectively.

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1. Introduction

With increasing concerns about climate change, peak oil and rising energy costs, oil dependent communities, particularly off-grid communities, should explore renewable energies. The historic price trend of diesel and gasoline shows that continuous demand, heavy resource extraction and political instability together push the oil prices ever higher. Power generation is one of the largest contributors to GHG emissions that fuels global climate change [1]. Small-scale diesel generators (50–100 kW) are only 25–35% efficient. Since costs for fuel in the remote off-grid communities, with diesel generation and freight costs, are three times more expensive than fuel prices elsewhere in Canada, due to transportation costs, renewable energy technologies (RETs) may make more economic sense in remote off-grid communities. Presently, small-scale diesel generators provide power to over 300 off-grid communities in Canada with a combined population of over 200 000 people [2]. This study looks at the feasibility of sustainable, reliable energy supply in off-grid communities by conducting a life-cycle analysis of different energy systems in Northern Ontario's Experimental Lakes Area (ELA).

Currently at ELA, diesel generates electrical power at the high energy cost of $0.230/kW, resulting in GHG emissions of ~280 t CO_2 annually. In addition, propane heats most building at an additional cost. ELA is considering reducing its emissions and costs through demand side management (DSM) and supply side

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management (SSM), including the consideration of RETs. Energy saving measures, retrofitting, and downsizing of equipment are DSM measures. Being expensive per kW, RETs always require that DSM be considered to reduce peak load, which reduces initial costs, as well as on-going fuel costs [3].

Since the early 1990's there have been significant developments in various RETs for commercial, industrial and residential sectors, which make them competitive with fossil fuels. RETs have advantages over non-renewables that include low energy cost, oil independence and pollution free generation, but also have disadvantages, which include reduced reliability and high initial cost. Energy sources, such as wind and solar require back-up by a stable source, if there is no grid connection to guarantee reliable power supply [3]. A reserve capacity is necessary to act as a back-up to overcome fluctuations and reliability issues with wind and solar intermittent sources that do not generate energy when the wind is not blowing or the sun is not shining [4]. Although RETs do not burn fossil fuels, they often require back-up systems that do. All renewable energies require that resource availability be compared to the loads to determine if the site specific production meets the local need. RETs combined with energy storage systems provide a reliable energy supply, which is the highest priority in the design of an isolated power system [3]. Natural energy flows vary and make the techno-economic performance of renewable energy conversion highly site specific. There are a host of renewable energies, including wind power, solar PV, biomass, etc., but are any feasible at the ELA specific location? The benefits and applications of these RETs in Canada will be profiled to consider their feasibility.

Wind power is a clean renewable energy but is intermittent requiring wind–diesel hybrid systems to provide a stable capacity. At ELA, wind power is considered feasible because mean annual wind speeds are 4–5 m/s. With a battery storage unit the hybrid wind power system, with a back-up diesel system, could mitigate diesel consumption by about 30–40% annually. With a current installed capacity of 327 MW, wind is a small contributor to Canada's RETs compared to 69 000 MW hydropower. However, wind is one of the fastest growing sources of electricity generation in Canada; the average annual growth rate in wind energy capacity is over 27% per year.

Currently, solar PV modules with battery back-up are effective in meeting power needs in remote locations for homes, cottages as an alternative to installing new transmission lines or diesel generators. The solar resource in Canada compares favorably with other regions of the world, due in part to its "clear-sky" climate. Canada's installed PV capacity is ~13 MW, and is forecasted to reach 200 MW by 2015. At ELA, solar radiation is approximately 3.72 kWh/m^2/day [5]. Although there are many possible applications of solar energy including water heating, passive heating and space cells made of semiconductor materials like silicon, that can convert solar energy to electricity with 10–20% efficiency [6]. Solar generation is a good match to energy demands at ELA as during summer; when ELA has the highest power demands, extended daylight hours produce the maximum power, while in winter shorter daylight hours produce minimum power when power loads at ELA are small.

Wood based energy generation units can use the surplus bio-residue to produce heat and power simultaneously in a system called combined heat and power (CHP). In biomass based CHP, both heat and power are generated from biomass with a back-up system of diesel generators to handle peak load demands. Biomass resources are typically forestry products such as wood waste or wood pellets but can include agricultural residues, landfill gas, municipal solid wastes and energy crops. Small-scale biomass CHP have been used extensively in space and water heating for housing, process heat for industry since the 1940s in Sweden, Finland and other Baltic states like Latvia, Estonia, and Lithuania [7]. Approximately 6% of Canada's primary energy is from biomass energy in the form of combustion of wood and wood derivatives for industrial process heat, generation of electricity, and space heating. Canada, with over 2.4 million km^2 of forests, has good potential to provide remote areas with a renewable source of energy [8]. At ELA, dead wood from the nearby forest could provide sufficient biomass and its their collection would reduce the risk from forest fire and costs of clearing for fire suppression reduce the cost of maintenance for fire supression system and clearing cost. Suppliers retail biomass at ~$200/ton.



Fig. 1. Ariel view of facility showing the field station surrounded by woods and lakes.

1.1. Study area

The study area is the Experimental Lakes Area (ELA) field station located 50 km south of Kenora, Ontario close to the Manitoba border in Canada. This northern location at latitude 49°, 47 min and 15 s north varies in weather from +30 in the summer to −30 °C in the long winter. The field station includes 20 buildings which are mainly clustered around the laboratory and kitchen. In 2001 three new buildings were added to the facility, namely, a laboratory and two new R-2000 residences. Each residence has common areas and ten or so single ten or so single rooms. Some buildings date back to 1968. In total, about 6900.00 square feet of laboratory space is available (see Fig. 1 for an aerial view of ELA) [9].

2. Method

RET Screen International 4.0® was used to compare the feasibility of three different RETs to diesel generation. RET Screen is a renewable energy decision-support and capacity-building tool developed by Natural Resources Canada (NRCan) with the contribution of 85 experts including from United Nations Environment Programme (UNEP) and the National Aeronautics & Space Administration (NASA). This standardized and integrated renewable energy project analysis software evaluates the energy production, life-cycle costs and GHG emission reductions for various types of RETs. The computer program, RET Screen, provides a common platform ideal for educational purposes and industry/market analysis and development purposes and is free of charge [10]. The following three steps were applied in RET Screen:

Step 1 Evaluated the present energy, economic and environmental situation by referring to ELA fuel bills, manuals, and audit reports. Data on diesel, propane, and gasoline consumption were gathered from the facility log books. Preliminary data about installed electrical and mechanical equipment were

Table 1
Energy system model scenarios.

Energy scenario	Battery	Resource assessment	RET
I – 100 kW (wind–diesel system)	Days of autonomy – 5.0 Voltage – 48.0 Efficiency – 85% Maximum depth of discharge – 60% Charge controller efficiency – 95% Temperature control method – constant Battery temperature – 24.0 °C Average battery temperature derating – 0.4% Capacity – 12 000 Ah Battery – 576 kWh	Wind speed measured at – 10 m Wind shear exponent – 0.30 Air temperature – 2.5 °C Atmospheric pressure annual – 96.5 kPa	Power capacity per turbine – 100 kW Manufacturer – Northern Power Systems Model – NW100/19–25 m Number of turbines – 1 Power capacity – 100 kW Hub height – 25 m Rotor diameter per turbine – 19 m Swept area per turbine – 284 m^2 Energy curve data – standard Shape factor – 2.0
II – 100 kW (solar PV–diesel system)	Days of autonomy – 4.0 Voltage – 48.0 Efficiency – 85% Maximum depth of discharge – 60% Charge controller efficiency – 90% Temperature control method – ambient Average battery temperature derating – 10.3% Capacity – 10 000 Ah Battery – 480 kWh	Solar tracking mode – fixed Slope – 50.0 Azimuth – 40.0	Type – Mono-Si Power capacity – 100.00 kW Manufacturer – GE Model – Mono-Si – AP – 120 Efficiency – 12.3% Nominal operating cell temperature – 45 °C Temperature coefficient – 0.40%/°C Solar collection area – 812 m^2 Control method – maximum power point tracker
III – 100 kW (Biomass with diesel back-up)	No battery needed Peak load power system Technology: reciprocating engine Fuel type: diesel (l) Fuel rate: ($/l): 0.8 Suggested capacity: 0.0 kW Capacity: 114 kW Back-up power system (optional) Technology: reciprocating engine Capacity: 114 kW	Power Base load power system Technology – other Operating strategy – Power load following Capacity – 100 kW Electricity delivered to load – 496 MWh Electricity exported to grid – 0 MWh	Heating Base load heating system Technology – other Capacity – 130.0 kW Heating delivered – 92 MWh

gathered from manufacturer's manuals, previous studies and interviews with the field manager and other key personnel at ELA. Data from different consultant's reports on alternative energies were gathered [11–13] but none of these reports considered biomass or DSM.

Step 2 Performed a modified Manitoba Hydro energy efficiency audit of the field station which involved counting light bulbs and determining equipment loads for six buildings. This audit included interviews and a walk through tour noting characteristics, usage and amounts of: (1) bulk fuel use; (2) building envelope (quality of sealing of windows, doors); (3) lighting (load); (4) heating, ventilation and air conditioning (kW/h); (5) office and lab equipment (usage and quantity); and (6) other machines and equipment (usage and quantity). The current energy consumption was estimated from the audit, as no metering was installed on site, to identify direct low cost energy conservation measures.

Step 3 Applied the present-day load minus the 20% energy efficiency determined in step 2, *Method-two* in RET Screen was undertaken to ascertain the technological, cost, emissions and risk analysis on the three RETs. Table 1 shows the RET Screen model inputs applied to determine feasibility.

Table 2
Economic and financial parameters for RETs.

Parameter	Wind–diesel Hybrid	Solar PV–diesel Hybrid	Biomass
Initial costs ($)	373 784	572 070	283 989
O & M ($/year)	29	2 400	2 190
Fuel cost–proposed case ($/year)	41 449	56 139	63 729
Fuel cost–base case[a] ($/year)	98 067	97 071	151 881
Debit ratio (%)	75	75	75
Debt interest rate (%)	7.00	7.00	7.00
Debt term (years)	10	10	15

[a] Biomass replaces both diesel and propane.

Step 4 The three different RET scenarios were calculated based on parameters in Table 2. As well the following were considered:

1. Local climatic data (solar radiation, wind speed, ambient air temperature, humidity).
2. The assumption that any new load will be balanced by increased energy efficiencies.
3. Diesel price of $0.80/l, propane price of $0.45/l.
4. Higher heating value (HHV[1]) as ELA is in a northern climatic zone with an average winter temperature of −17.4 °C and reaches above 30 °C in the summer for reference year 2006. Its occupancy varies from full capacity of 40–45 people in the summer to about 3–5 people in winter.

3. Findings

An energy map of ELA shows the smaller amount of propane and gasoline used compared to diesel. Fig. 2 summarizes the annual total input and output energy at ELA for the 2006/2007 fiscal year. The existing system has a total peak power generation of nearly 115 kW and a total operating cost of $84 821/year. Most of GHG emissions and energy costs at ELA are for electricity production from diesel fuel. Only one-fifth of the fuel costs are from heating with propane. The demand for electricity could be reduced with energy efficiency which decreases the cost of capital equipment.

[1] ELAs geological location requires the model to be simulated in a higher heating value setting.

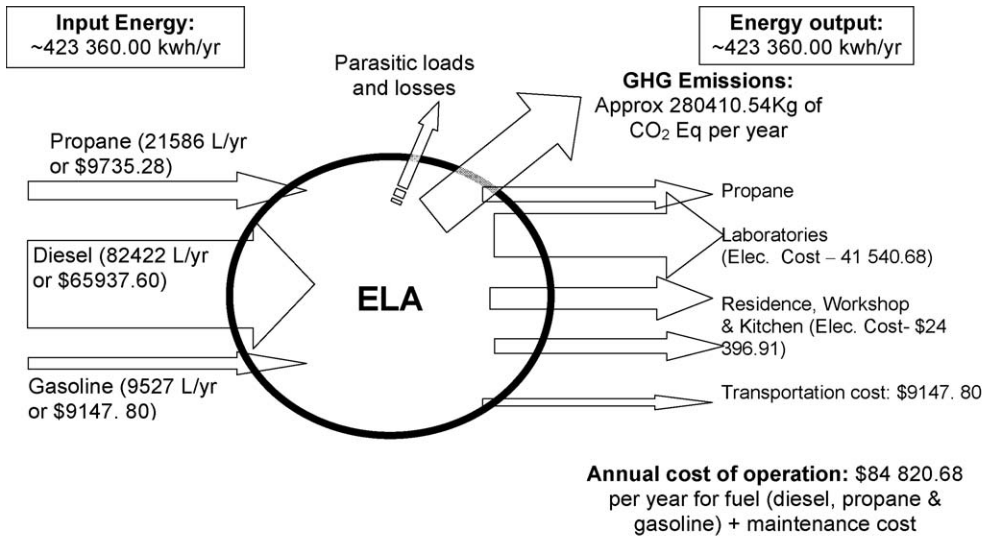


Fig. 2. Energy Map of ELA revealing the flow of energy through the facility for the 2006/2007 fiscal year.

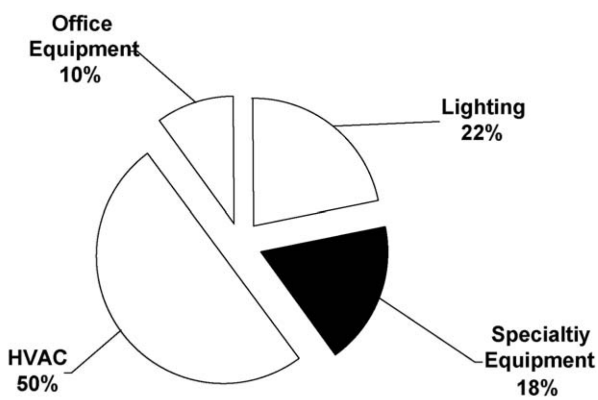


Fig. 3. The electrical energy breakdown indicates that HVAC and lighting combined consume two-thirds of the total power.

3.1. Energy efficiency

With almost 80% of total fuel being consumed for electricity production, as shown in Fig. 3, DSM can make a difference in energy requirements. Table 3 shows many opportunities to reduce energy, identifying key areas for energy measures including exit lights, lights and the ice maker. DSM can reduce energy use by 15% to 20% of the existing energy consumption, which amounts to 92500 kWh or $22 865 in savings annually. The DSM savings are based on all twenty buildings being retrofitted and behavioural/ operational changes. Payback periods ranged from as little as 4 months for lamps to about 20 years for refrigerators. Other areas such as the building envelope appeared adequate. Table 3 shows that significant savings can be made from shifting to more energy efficient lights, refrigerators and other low cost measures.

The results of RET for the three models are shown in Table 4. Renewable energy technologies were economically competitive with the diesel system, particularly the biomass CHP system. At $0.80 cents/l, biomass' combined heat and power (CHP) payback period was 4.1 years with a capital cost of $1800/kW compared to wind's 6.1 years due to its higher initial cost of $3300/kW and solar's 13.5 years due to its high initial cost of $9100/kW. The CHP had an initial cost for equipment (hopper, conveyor belt and gasifier but not including piping for district heating) at $1800/kW with an energy cost of $0.12/kW. The payback for CHP is much less at higher diesel prices of $1.20/l and $2.00/l, respectively at 1.8 years and 0.9 years.

When a liter of diesel approaches $1.20, power generation by diesel generation costs $0.55–0.70/kW. When the price of diesel is at $2.00/l the cost of electricity from diesel is approaching $0.89/

Table 3
Summary of DSM recommendations with savings.

Problem Identified	Recommendations	Capital cost of recommendation ($)	Energy savings (kWh)	Energy savings ($)	Pay back period
32 lights in labs	Replace the five all existing incandescent lights with LED and/or CFL	7 000	79 200.00	19 800.00	Under 4 months
Exit Lights	Replace all seven exit lamps in 20 buildings with LED exit lights	3 150	6132.00	530.00	~2 years
Two, old 40 cubic foot refrigerators	Replace both old with Energy star[a] units	2 × ~$7500.00 = $15 000.00	30% saving on 9066.6 (existing)[b]	518.00	>20 years
Oversized ice maker (1100 W)	Downsize to a smaller (575 W) unit	Approx $2500.00	50% savings on 4876.7 (existing)[c]	580.00	4.3 years
Two ovens running continuously at 90 °C	Turn off one oven during nights	$0.00	25% savings on 6832.8 (existing)[d]	437.00	n/a
Total		$27 650	92500	22865	

[a] Saves at least 20%.
[b] A saving of $2719.98.
[c] A saving of $2438.35.
[d] A saving of $1708.20.

Table 4
RET Screen analysis of the three scenarios at different diesel prices.

Parameters	Electricity				Heat and power	Heating	
	Solar power[a]	Wind power[a]	Diesel power	New diesel generators	Biomass	Geothermal heating	Propane heating
	100 kW	100 kW	115 kW (existing)	115 kW	100 kW		
Reliability	Low-moderate	Low-moderate	High	High	High	High	High
Availability	∼25–30%	∼25–30%	<95%	<95%	<95%	–	<95%
Avg. initial cost ($/kW)	9100	3300	–	∼160	1800	n/a	n/a
Cost of power (in $/kW)	0.045	0.145	0.225	0.200	0.120	0.083	0.454
Efficiency	12.3%	∼30%	∼25%	∼30%	∼85%	>85%	∼85%
Equity pay back period (years) at different diesel prices	13.5 @ $0.8/l 6.7 @ $1.20/l 3.2 @ $2.0/l	6.6 @ $0.8/l 3.6 @ $1.20/l 1.8 @ $ 2.0/l	–	–	4.1 @ $0.8/l 1.8 @ $1.2/l 0.9 @ $2.0/l	4.7	–
Capital cost ($)	910 000	330 000	–	16 000	180 000 without district heating network 207 000 with district heating network	26 000	–
Annual fuel cost ($) at different diesel prices	Nil	Nil	$65 937.60 @ $0.8/l $98 906.40 @ $1.2/l $164 844.00 @ $2.0/l	$65 937.60 @ 0.8/l $98 906.40 @ $1.2/l $164 844.00 @ $2.0/l	∼6500.00	3039.00	$9735.28 @ 0.8/l $25 903.20 @ 1.2/l $43 172.00 @ 2.0/l
GHG emission reduction (t CO_2)	187	134			497		
Carbon tax savings @ $10/ton/year	$1870	$1340			$4970		
Carbon tax savings @ $50/ton/year	$9350	$6700			$24 850		

[a] RET.

kWh. This is twice as expensive as wind generation, seven to eight times as expensive as biomass generation and about nineteen times as expensive as solar power per kWh. Other fuels become very affordable and the payback periods are greatly reduced at these higher diesel prices. At $1.20–2.00/kWh for diesel, the payback periods (years) of different RETs are, respectively: 1.8 years to 0.9 years for CHP, 3.6 years to 1.8 years for wind, and 6.7 years to 3.2 years for solar.

RETs will reduce greenhouse gas (GHG) emissions considerably by an estimated 187 tons per year by a wind–diesel hybrid system, 134 tons per year by a solar PV–diesel hybrid system and 497 tons per year by the biomass system. Biomass CHP is a reliable technology and burning wood is considered a sustainable cycle as the carbon burned will be used up when new trees replace them, as long as the forested area's land use is unchanged from forest. Concerning power generation, the existing diesel system is inefficient at ∼25% and is expensive to generate at $0.23/kW, which is much higher than wind power at $0.14/kW, solar power at $0.045/kW and biomass at $0.12/kW, not considering capital costs. Wind and solar technologies are considered to be zero emission technologies during power generation while both diesel and biomass emit pollution including GHG at the site of generation. However, biomass based power generation is a carbon neutral technology, as trees that replace those burned take up the carbon emitted during combustion if the land remains forest. Based on the initial cost for equipment, solar PV at $9100/kW is the most expensive among the technologies, requiring a long payback period of 13.5 years. At $3300/kW, wind power is more expensive than installing a new diesel generator or implementing a biomass system.

Heat is a byproduct of the biomass CHP system, which could replace the propane expense of almost $9150 for heating the residences and laboratories. Network piping would increase the CHP system cost by an additional $27 000, as shown in Table 2. The payback of $27 000 would be faster than geothermal heating, which costs slightly less at $26 000 and would take 4.7 years to repay. Geothermal reduces propane use by two-thirds typically by using the earth's heat, whereas CHP heat is waste heat, not requiring any additional fuel.

4. Conclusion

Some RETs, particularly CHP at ELA, are feasible in off-grid communities, according to this study, and may soon be feasible in grid communities if fossil fuel prices increase as depletion occurs. The utility of applying DSM prior to sizing RETs was demonstrated by RET Screen at ELA from 115 kW to 100 kW, reducing initial costs by $27 000 for CHP, $49 500 for wind and $136 500 for solar. This study shows that DSM and SSM can be applied effectively to dramatically improve the energy situation at ELA resulting in lower energy cost and cleaner energy production. DSM can shave off at as much as 15% to 20% with a complete energy efficiency retrofit to the twenty buildings 92 500 kWh or $22 865 in savings annually.

Of the three RETs analyzed, biomass was found to be more economically and environmentally feasible than wind and solar for ELA. A biomass CHP system would reduce annual energy costs by $63 729 per year, including replacing propane heating and mitigating GHG emissions by over 98% to 10 t CO_2 from 507 t CO_2. Wind power generation is very competitive with biomass if not for its high initial cost and moderate reliability. Solar has the lowest feasibility due to the long payback period and high initial cost.

With biomass CHP a savings of about 50% can be achieved after 20% DSM. Also, with the existing diesel generators coming towards the end of their operating life, ELA is in an ideal situation to shift from fossil fuel towards a renewable fuel. As well, this research could benefit other off-grid communities, for which biomass is appropriate.

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